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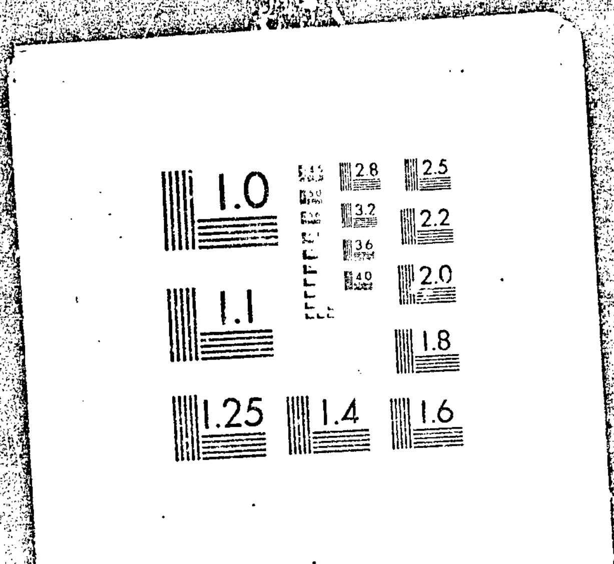

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VOLUME I
31 July 1980

FINAL REPORT

ORBIT TRANSFER VEHICLE ENGINE STUDY

EXECUTIVE SUMMARY

Contract NAS8-33444

Prepared for
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

PRATT & WHITNEY AIRCRAFT GROUP
Government Products Division
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UNITED TECHNOLOGIES ®

FOREWORD

The technical report presents the results of the Orbit Transfer Vehicle Engine Study. This study was conducted by the Pratt & Whitney Aircraft Government Products Division of United Technologies Corporation for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, under Contract NAS8-33444.

The results of the study are contained in three volumes, which are submitted in accordance with the data requirements of Contract NAS8-33444.

Volume I — Executive Summary
Volume II — Technical Report
Volume III — Program Costs

This study was initiated in July 1979, with technical effort being completed in 8 mo and the delivery of the final report on 1 May 1980. The study effort was conducted under the direction of the George C. Marshall Space Flight Center Science and Engineering organization, with Mr. Dale Blount as Contracting Officer's Representative. This effort was carried out by Pratt & Whitney Aircraft Government Products Division under the direction of Mr. J. R. Brown, Study Manager.

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SECTION 1

INTRODUCTION

The Orbit Transfer Vehicle (OTV) is planned as a high-performance propulsive stage which can be used, in conjunction with the Space Shuttle, to deliver/support large payloads/platforms to geosynchronous earth orbit (GEO) and other orbits beyond low earth orbit (LEO). Its role is similar to that of the "full capability" Space Tug defined in 1974 with the primary difference that the OTV will eventually be man-rated.

Studies either underway or planned by NASA are intended to provide the essential data to identify viable approach(es) and concept(s) which can fulfill the projected OTV mission requirements. These studies must also define the timing at which the various capabilities are required, such as initial unmanned cargo delivery, rendezvous and return of payloads, manned GEO sortie missions, etc. This information, in addition to projected budgetary considerations, will be used to determine the OTV development approach (evolutionary/phased/direct development, etc.)

In order for vehicle systems studies to cover the full range of OTV concepts, it is essential that data on the complete spectrum of propulsion systems be available. This study addressed the propulsion system spectrum by covering candidate OTV engines from the near-term RL10 (and its derivatives) to advanced high-performance expander and staged combustion cycle engines. The results of this study, combined with the concurrent vehicle system studies, should permit an early screening of the OTV concepts and permit design point studies to be initiated for both engine and vehicle.

SECTION 2

STUDY SUMMARY

2.0 STUDY OBJECTIVE

The objectives of the Orbit Transfer Vehicle (OTV) Engine Study were to provide parametric performance, engine programmatic, and cost data on the complete propulsive spectrum that is available for a variety of high-energy, space-maneuvering missions. This was to be accomplished to provide this information to the vehicle systems contractors to be used during their concurrent studies.

2.1 STUDY TASKS

The activities to accomplish the study objective were broken into seven tasks. A study plan flow diagram identifying the relationship of each study task is shown in Figure 2-1. The tasks and work accomplished under each are:

1. Task 1 — RL10/Derivative Engine Data — The "Design Study of RL10 Derivatives" (NAS8-28989) was completed in 1973. This study was reviewed and updated to incorporate the effects of improvements in performance prediction techniques, inflation, and other influencing factors that have developed since that study was completed. Also, low-thrust operational characteristics of the RL10 derivative engines were reviewed to define the impact of extended low-thrust operation.

2. Task 2 — Parametric Engine Data — Parametric engine data (performance, weight, envelope, and cost) were generated for advanced expander and staged combustion cycle engines. Prior to generating the parametric information, preliminary cycle studies were completed to define ground rules and allow selection of a viable engine configuration of each type as baseline engines. The parametric data was then generated using the selected advanced expander and staged combustion cycle engine baseline configuration.

3. Task 3 — Programmatic Analysis Planning and Cost Estimate — A detailed programmatic analysis was conducted to provide the initial project planning by producing schedule and cost data for the selected engine concept, as defined in Task 4. In order to provide programmatic data, items such as hardware lead times, milestone scheduling, type of testing, facility requirements, and projected costs were compared to previous RL10 engine history. The overall engine project data was then divided into development, production, and operational support categories.

4. Task 4 — Advanced Expander Optimization — Performance was optimized for advanced expander cycle engines with thrust levels of 10, 15, and 20K lb at a mixture ratio of 6:1, with a maximum engine retracted length of 60 in. The preliminary cycle studies completed as part of the parametric engine data generation (Task 2) provided the starting point for the optimization. The baseline expander cycle configuration was used to optimize the combustion chamber/primary nozzle configuration (chamber

length, contraction ratio, coolant passage dimensions, etc.). In addition, other cycle studies were conducted to define cycle variations that may provide performance improvements. These results were evaluated considering performance-weight trade factors, life requirements, impact of control requirements, and chilldown/start losses. A preliminary point design engine configuration was determined for each of the three thrust levels and used to generate power balance points.

5. Task 5 — Alternate Low-Thrust Capability — The 15K-lb thrust optimized design-point engine (Task 4) was used to determine the design impact of adaptation to provide extended low thrust (1.5K lb) operation. The operational characteristics at low thrust of the selected engine configuration were generated to define the critical components for extended low-thrust operation. Performance characteristics and cycle parameters were defined and used to determine if kitting of critical components provides a significant advantage, or if adequate capability is provided by control modification.

6. Task 6 — Safety and Reliability Comparisons — In-depth analyses of crew safety and mission reliability were made on the optimum expander cycle engine, as detailed in Task 4, and on the staged combustion OTV engine detailed in NAS8-32996 to provide a direct comparison of these items for the staged-combustion and expander-cycle concepts. Both engine systems were compared on OTV employing 1, 2, and 3 engines.

7. Task 7 — Vehicle Systems Studies Support — The data generated in the RL10 Derivative Update (Task 1) and Parametric Engine Data (Task 2) was compiled into a Parametric Data Book, published and delivered to NASA 3 months after start of this study. The information contained in the document was to be used by the vehicle systems contractors during their concurrent studies.

The study was initiated in July 1979, and the technical effort was completed in February 1980. The schedule achieved in this study for seven tasks is shown in Figure 2-2.

This final report consists of three volumes:

Volume I — Executive Summary
Volume II — Technical Report
Volume III — Program Costs

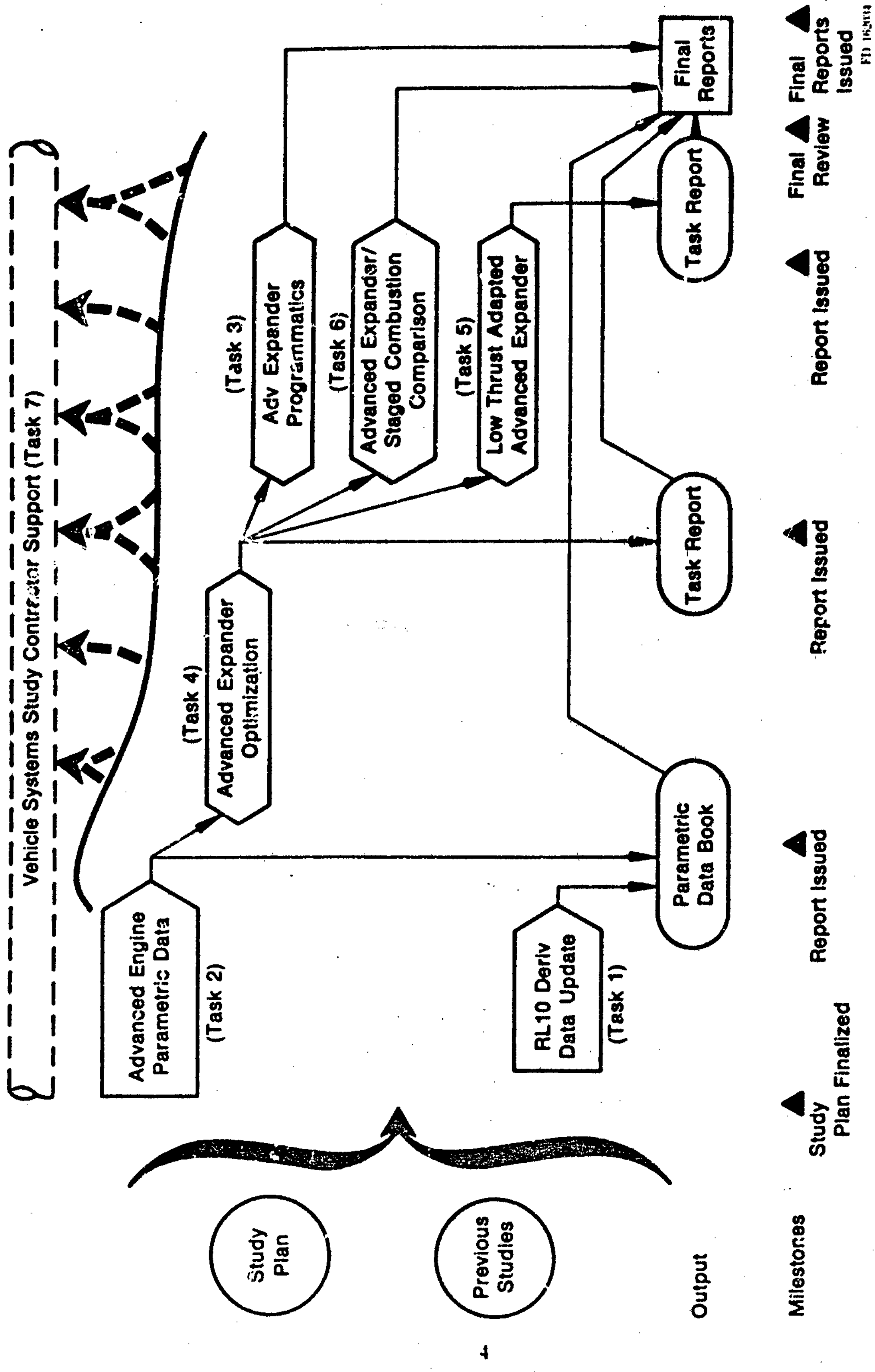


Figure 2-1. OTV Engine Study Flow Diagram

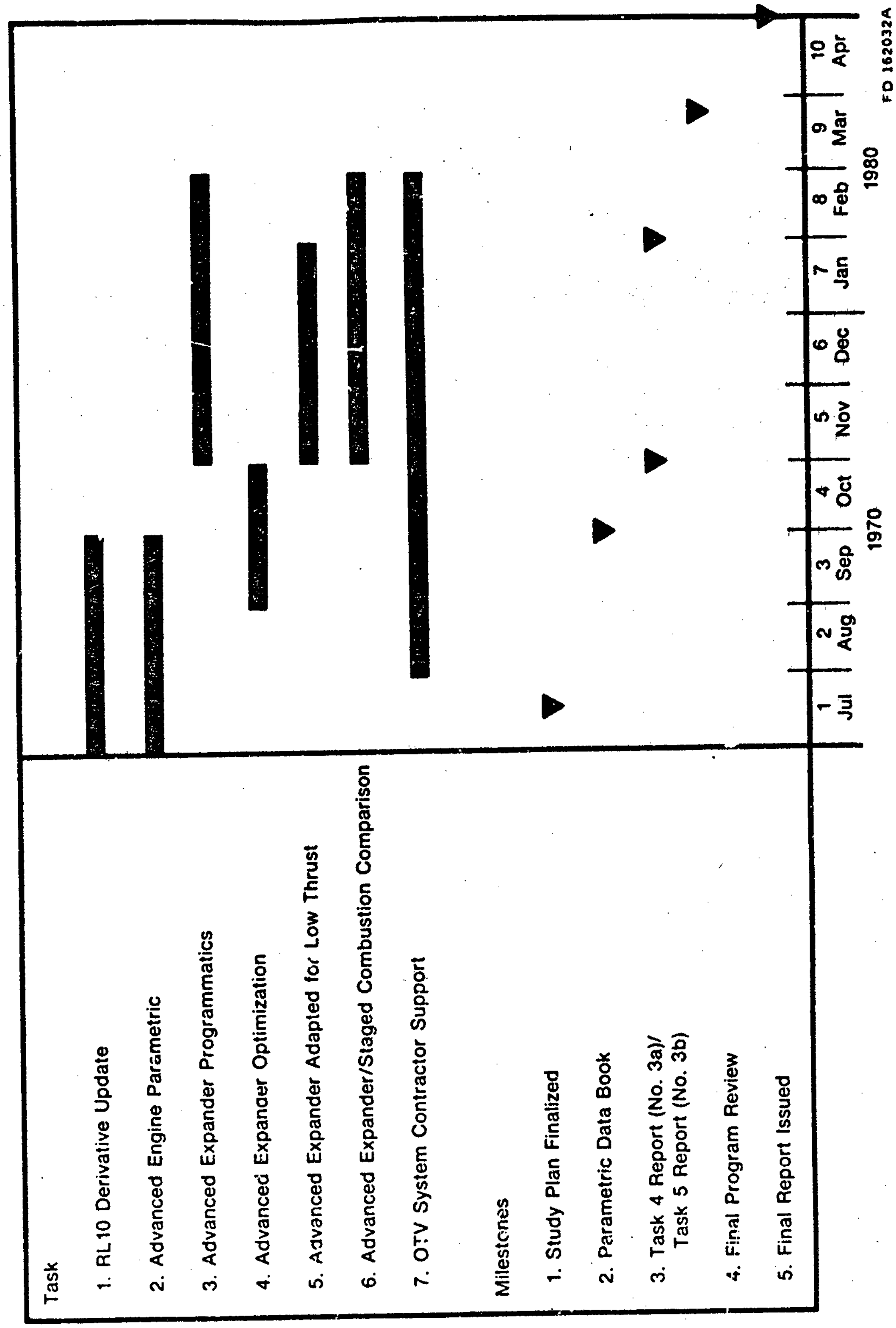


Figure 2-2. Orbit Transfer Vehicle Engine Study Schedule

2.2 STUDY RESULTS

The results of this study are presented in the following paragraphs.

2.2.1 Baseline Engines

Three of the engines defined under Contract NAS8-28989 (the RL10 Derivative IIA, IIB and Category IV) were included in this study and were updated to reflect improvements in performance predictions, addition of a carbon-carbon extendible nozzle, and inflation.

In addition, the Derivative IIC was defined as a moderately high-performance engine for use in an early expendable OTV and an advanced expander cycle engine was defined as a 1980 state-of-the-art OTV engine candidate. The baseline engine design points are summarized in Table 2-1, and a brief description of the performance and operating characteristics of the engines are given in the following paragraphs. More detailed descriptions are provided in Volume II of this report.

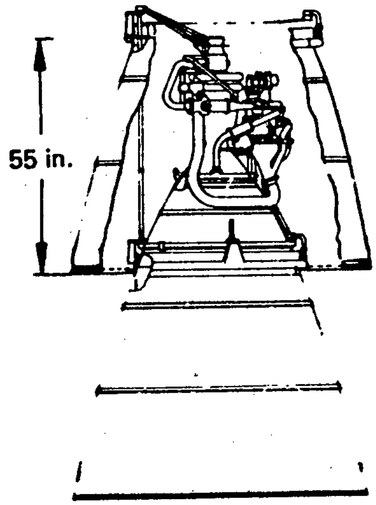
TABLE 2-1. BASELINE ENGINE DESIGN POINTS

	Derivative IIA	*Derivative IIB*	*Derivative IIC*	*Category IV*	*Advanced Expander*
Full Thrust (vac), lb	15,000	15,000	15,000	15,000	15,000
Mixture Ratio	6.0	6.0	6.0	6.0	6.0
Chamber Pressure, psia	400	400	400	915	1505
Specific Impulse, sec.	459.8	459.8	458.6	471.7	482.0
Required Inlet Conditions (Full Thrust)					
Fuel, NPSP, psi	0	0.5	2	0	0.5
Oxidizer, NPSP, psi	0	4	4	0	1
Installed Length, in.	55	55	55	55	60
Weight, lb	431	392	374	371	391
Nozzle Area Ratio	205	205	205	388	640
Engine Life, Firings/hr	190/5[1]	190/5[1]	10/1.25[2]	300/10[3]	300/10[3]
Engine Conditioning	Tank-Head Idle	Tank-Head Idle	Overboard Dump Cooldown	Tank-Head Idle	Tank-Head Idle
Maneuvering Thrust Capability (pumped idle)	Yes	Yes	No	Yes	Yes
Development Program					
Time to FFC, Mo.	64	58	37	80	89
Cost, $79M*	100	79	21	157	243

*Including propellant cost, without Fee.

1. Time Between Overhauls (TBO)
2. Expendable Mission
3. Design TBO

2.2.1.1 RL10 Derivative IIA Engine



Thrust	: 15,000 lb
Chamber Pressure	: 400 psia
Area Ratio	: 205
I_{sp}	: 459.8 sec at 6.0 MR
Operation	: Full Thrust (Saturated Propellants)
	: Maneuver Thrust (Saturated Propellants)
Conditioning	: Tank Head Idle
Weight	: 431 lb
Life (TBO)	: 190 Firings/5 hr
DDT&E Cost	: $100 Million

FD 75662c

The RL10 Derivative IIA engine is derived from the basic RL10A-3-3, but has increased performance and operating flexibility for use in the OTV. With a nominal full thrust level of 15,000 lb (in vacuum) at a mixture ratio of 6.0:1, the Derivative IIA engine is defined as an RL10A-3-3 with the following changes:

1. Two-position nozzle with recontoured primary section to give a large increase in specific impulse with engine installed length no greater than the RL10A-3-3 (70 in.). With a truncated two-position nozzle installed, this engine has to be able to be installed and tested in the existing test facilities at P&WA/GPD.

2. Injector reoptimized for operation at a full thrust mixture ratio of 6.0:1.

3. Tank head idle (THI) capabilities, where the engine is run pressure fed without its turbopump rotating on propellants supplied from the vehicle tanks at saturation pressure. Propellant conditions at the engine inlets can vary from superheated vapor, through mixed phase, to liquid. The objectives are to supply low thrust to settle vehicle propellants and also to obtain useful impulse from the propellants used to condition the engine and vehicle feed system.

4. Operation at low thrust in pumped mode (maneuver thrust) but without significant impact on the engine's design. This thrust level was selected as 25% of full thrust in the previous study.

5. Two-phase pumping capability, allowing operation at both full and maneuver thrust levels with saturated propellants in the vehicle tanks and with no tank pressurization system or vehicle-mounted boost pumps.

6. Capability for both H_2 and O_2 autogeneous pressurization which may be required on very long-burn missions in order to avoid excessively low-propellant vapor pressure.

A propellant flow schematic at full-thrust operation is shown in Figure 2-3.

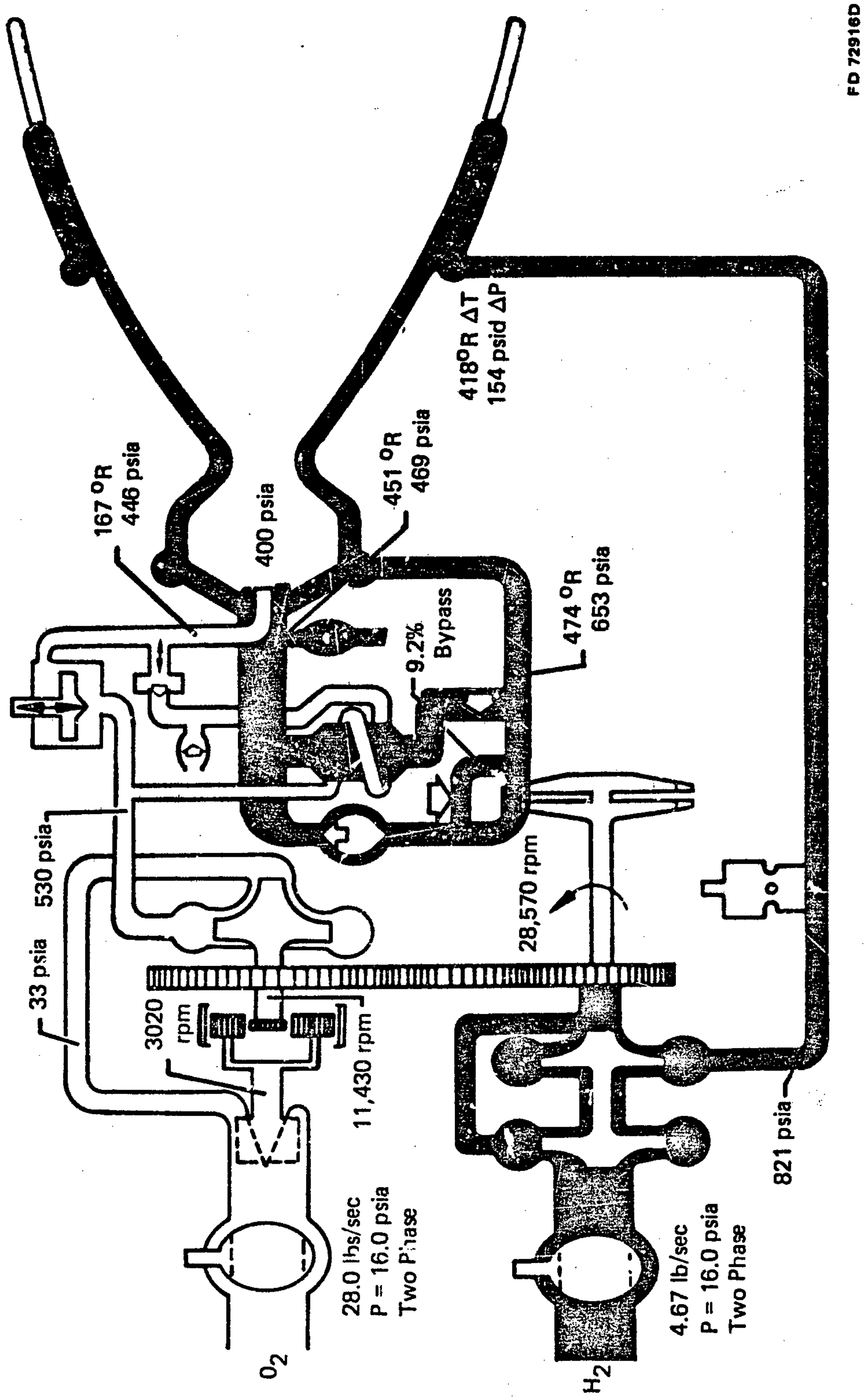
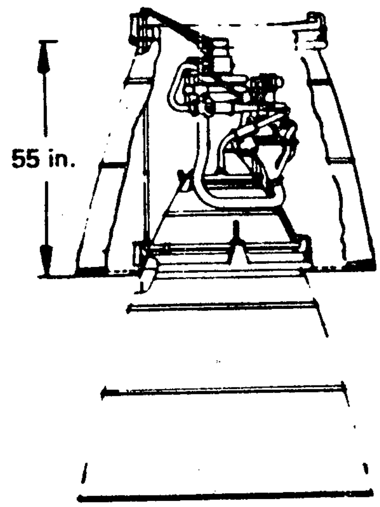


Figure 2-3. RL10 Derivative IIA Propellant Flow Schematic — Full Thrust (MR = 6.0)

2.2.1.2 RL10 Derivative IIB Engine



Thrust	: 15,000 lb
Chamber Pressure	: 400 psia
Area Ratio	: 205
I_{sp}	: 459.8 sec at 6.0 MR
Operation	: Full Thrust (Low NPSH)
	: Pumped Idle (Saturated Propellants)
Conditioning	: Tank Head Idle
Weight	: 392 lb
Life (TBO)	: 190 Firings/5 hr
DDT&E Cost	: $79 Million

The RL10 Derivative IIB is similar to the Derivative IIA engine except that it does not have the requirement for two-phase pumping capability at full thrust. The RL10 Derivative IIB is defined as the basic RL10A-3-3 engine with the following changes:

1. Two-position nozzle with recontoured primary section
2. Reoptimized injector
3. Tank head idle mode
4. Pumped idle mode, with saturated propellants in vehicle tanks, and bootstrap autogenous pressurization. This mode of operation allows the RL10A-3-3 Bill-of-Material turbopump to be run at a sufficiently low speed where prepressurization subcooling of the propellants at the pump inlets is not required. By using the engine's bootstrap autogenous pressurization capability, the tanks can then be prepressurized to satisfy the engine's full thrust pump inlet net positive suction head (NPSH) requirements before acceleration to full thrust.

A propellant flow schematic at full-thrust operation is shown in Figure 2-4.

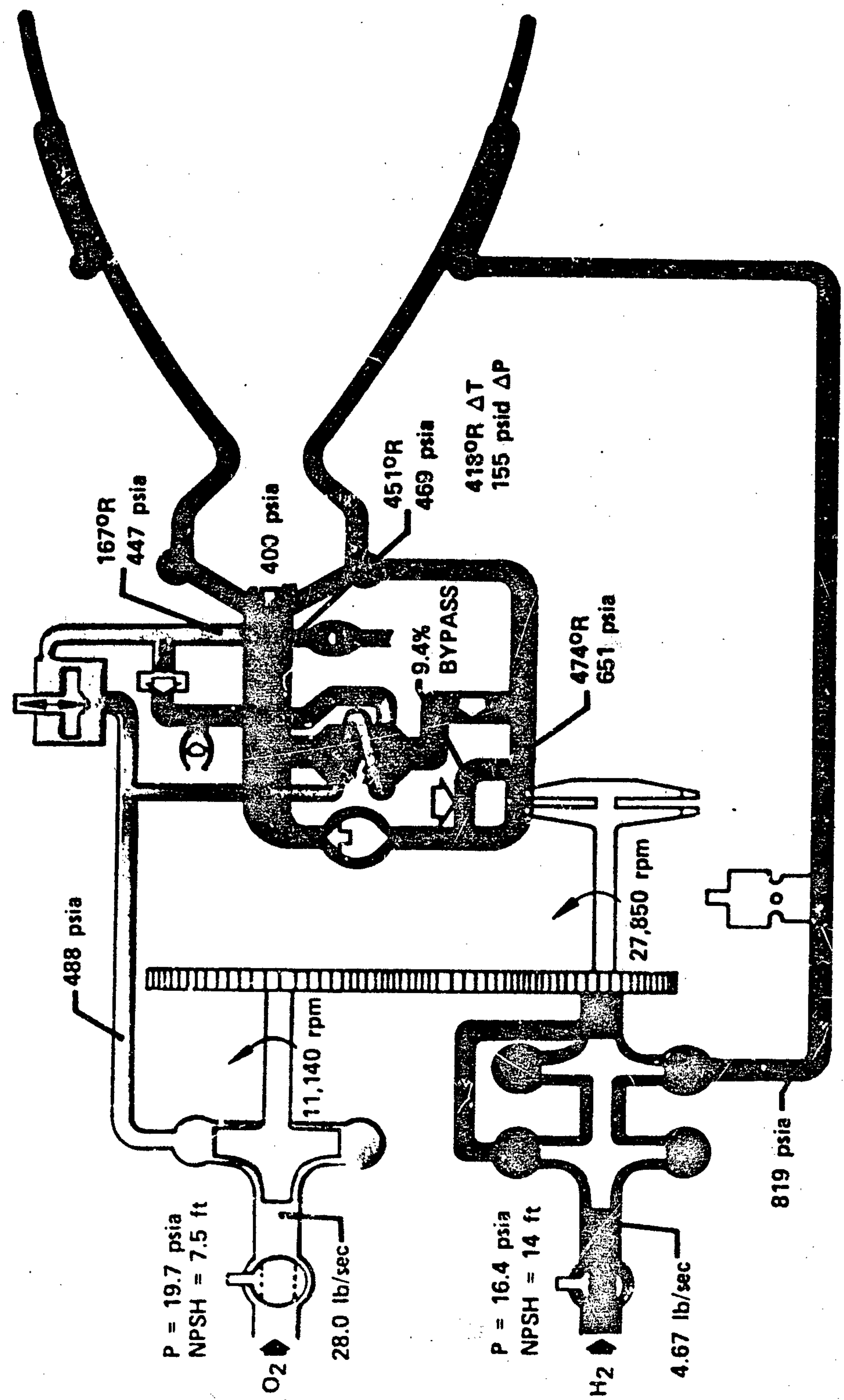


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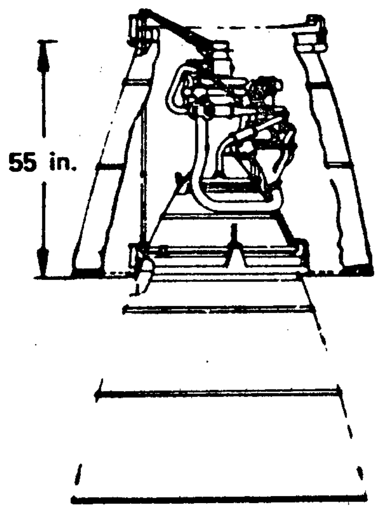
Figure 2-4. RL10 Derivative IIB Propellant Flow Schematic — Full Thrust (MR = 6.0)

2.2.1.3 RL10 Derivative IIC Engine



Thrust	:	15,000 lb
Chamber Pressure	:	400 psia
Area Ratio	:	205
I_{sp}	:	458.6 sec at 6.0 MR
Operation	:	Full Thrust (Low NPSH)
Conditioning	:	Overboard Dump
Weight	:	374 lb
Life (Expendable Mission)	:	10 Firings/1.25 hr
DDT&E Cost	:	$21 Million

FD 75083

The RL10 Derivative IIC engine is included in this report, even though it was not one of the engines defined in the original study, because it is a low-cost, high-performance candidate engine for an early expendable OTV. The RL10 Derivative IIC is the existing RL10A-3-3 engine, with the addition of a high-area-ratio, two-position nozzle and requalified to operate under OTV conditions. As a result, there are the following changes in engine requirements from those of the RL10A-3-3 Bill-of-Material engine:

1. Two-position nozzle with recontoured primary section
2. Mixture ratio increased to 6.0 (± 0.5)
3. H_2 autogenous pressurization
4. Increased life
5. 50% reduced NPSH limit and minimum pump inlet pressures reduced from 30 to 28 psia (H_2) and from 45 to 35 psia (O_2).

A propellant flow schematic at full-thrust operation is shown in Figure 2-5.

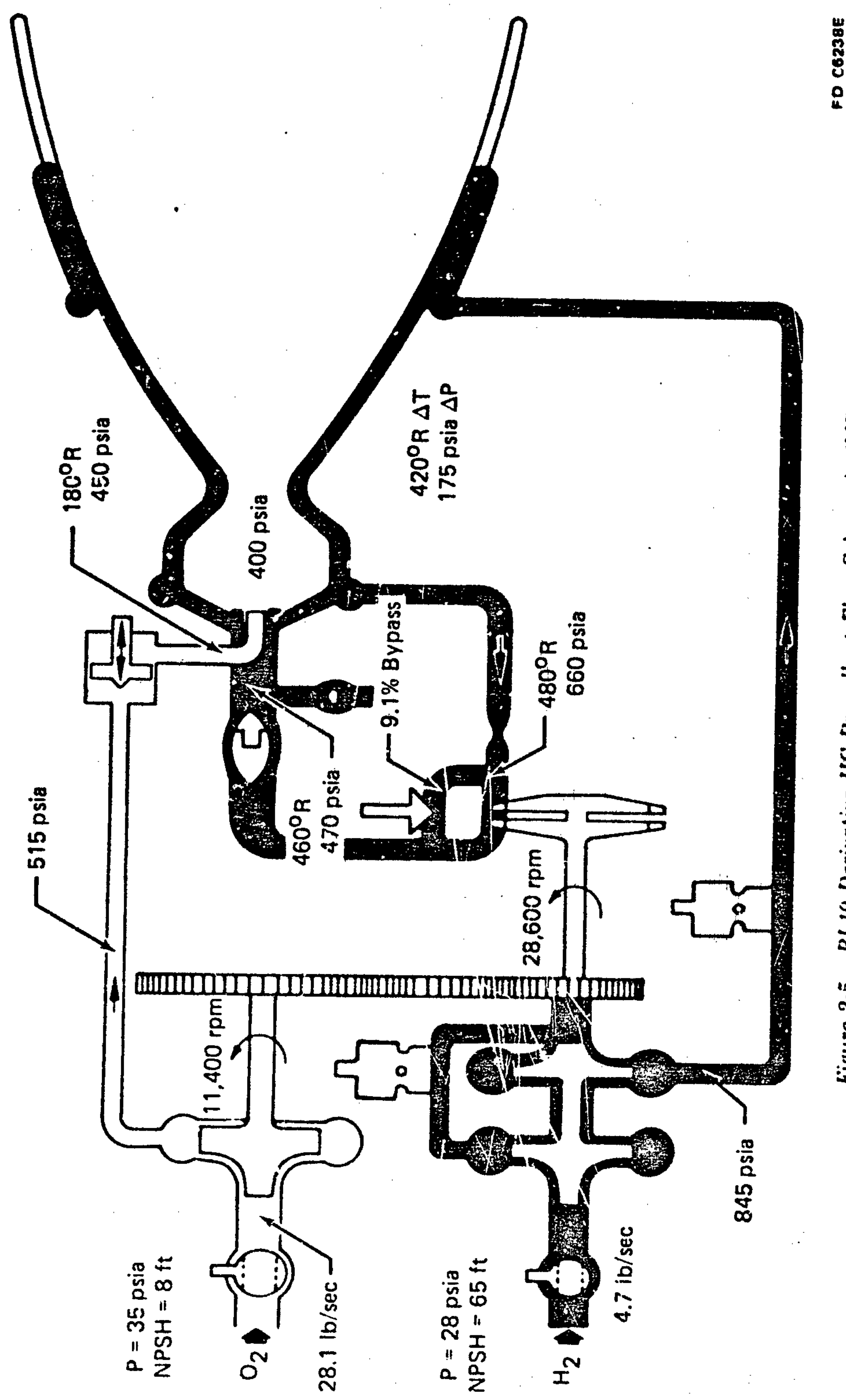
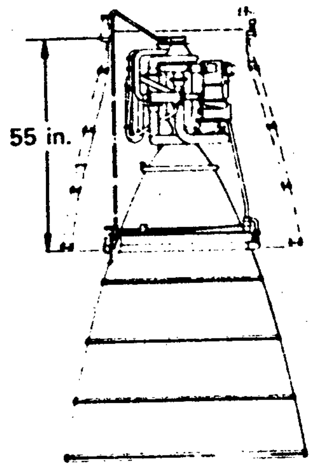


Figure 2-5. RL10 Derivative IIC Propellant Flow Schematic (MR = 6.0)

2.2.1.4 RL10 Category IV Engine



Thrust	: 15,000 lb
Chamber Pressure	: 915 psia
Area Ratio	: 388
I_{sp}	: 471.7 sec at 6.0 MR
Operation	: Full Thrust (Saturated Propellants)
	: Maneuver Thrust (Saturated Propellants)
Conditioning	: Tank Head Idle
Weight	: 371 lb
Life (Design TBO)	: 300 Firings/10 hr
DDT&E Cost	: $157 Million

FD 74124B

Unlike the Derivative II baseline engines, which are modified versions of the RL10A-3-3, the RL10 Category IV engine is a "clean sheet" design. However, it is not an advanced-technology engine, since it uses the same expander power cycle and basic design concepts of the RL10. Basically, it is a 1973 update of a design optimized specifically for use in the OTV. The baseline RL10 Category IV engine has the following requirements:

1. Interface requirements: interchangeable with RL10 Derivative IIA.
2. Operating modes: Same as RL10 Derivative IIA, i.e.,
   - Tank head idle mode
   - Maneuver thrust
   - Two-phase pumping capability at full thrust
3. Design life: 300 firings and 10 hr
4. Thrust level: 15,000 lb at 6.0 mixture ratio
5. Performance: optimize.

A propellant flow schematic at full-thrust operation is shown in Figure 2-6.

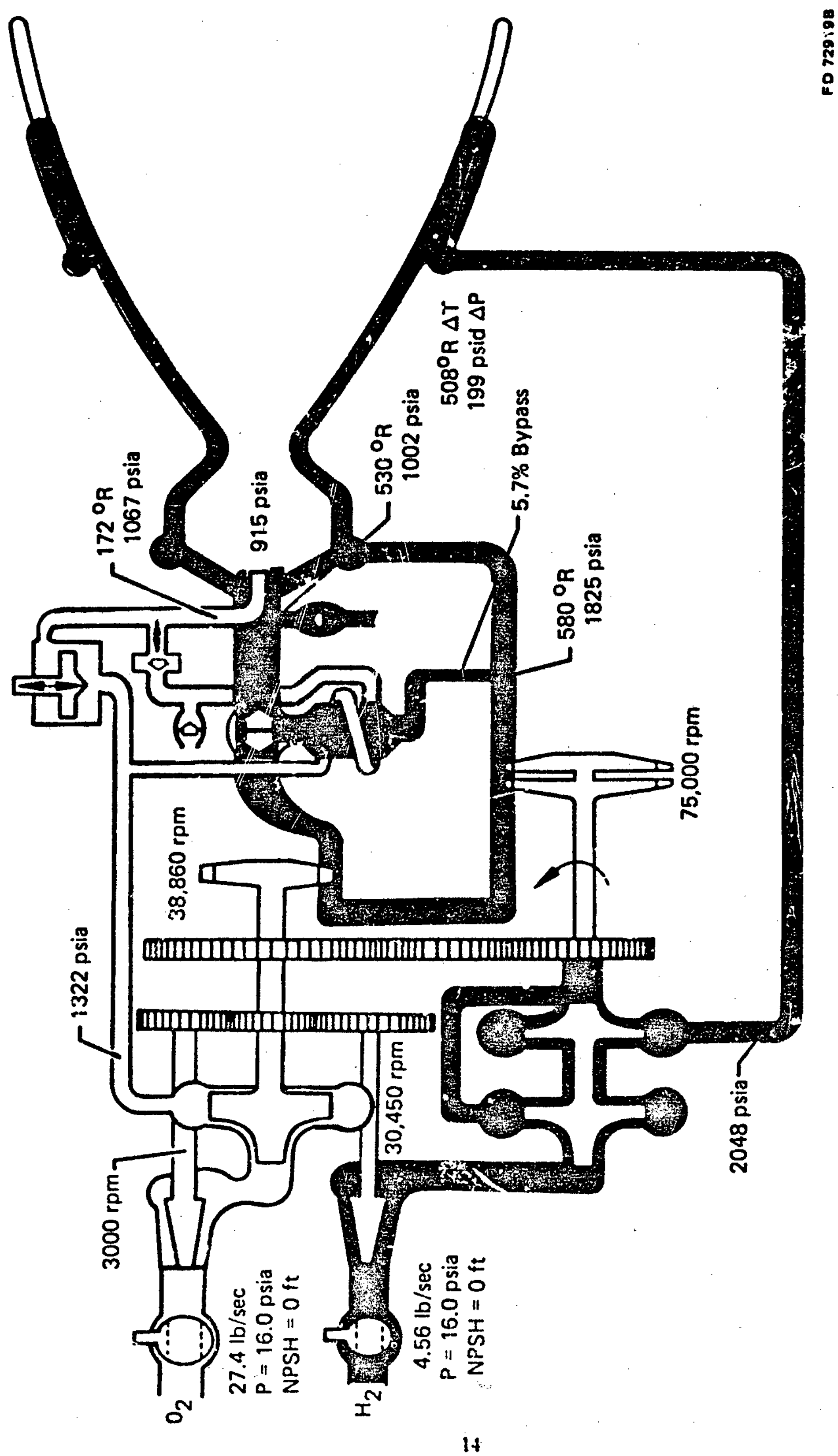
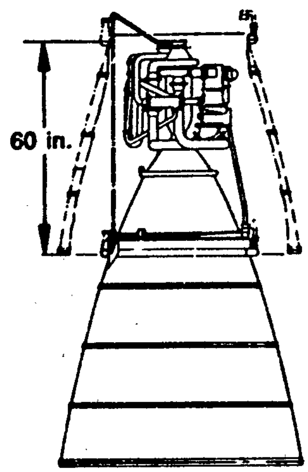


Figure 2-6. RL10 Category IV Propellant Flow Schematic — Full Thrust (MR = 6.0)

2.2.1.5 Advanced Expander Engine



Thrust	**: 15,000 lb**
Chamber Pressure	**: 1505 psia**
Area Ratio	**: 640**
I_{sp}	**: 482.0 sec at 6.0 MR**
Operation	**: Full Thrust (Low NPSH)**
	: Maneuver Thrust (Saturated Propellants)
Conditioning	**: Tank Head Idle**
Weight	**: 391 lb**
Life (Design TBO)	**: 300 Firings/10 hr**
DDT&E Cost	**: 243 Million**

FD 74124C

Like the RL10 Category IV engine, the Advanced Expander engine is a "clean sheet" design. Unlike the Category IV engine, it is an advanced-technology engine, incorporating improved pump and turbine designs, a carbon-carbon extendible nozzle, and a hydrogen regenerator. Basically, it is a 1980 state-of-the-art design optimized specifically for use in the OTV. The baseline Advanced Expander engine has the following requirements:

1. Interface requirements: not yet defined
2. Operating modes: Same as RL10 Derivative IIB, i.e.,
   - Tank head idle mode
   - Maneuver thrust
   - Low NPSH pumping capability at full thrust.
3. Design life: 300 firings and 10 hr
4. Thrust level: 15,000 lb at 6.0 mixture ratio
5. Performance: optimize

A propellant flow schematic at full thrust operation is shown in Figure 2-7.

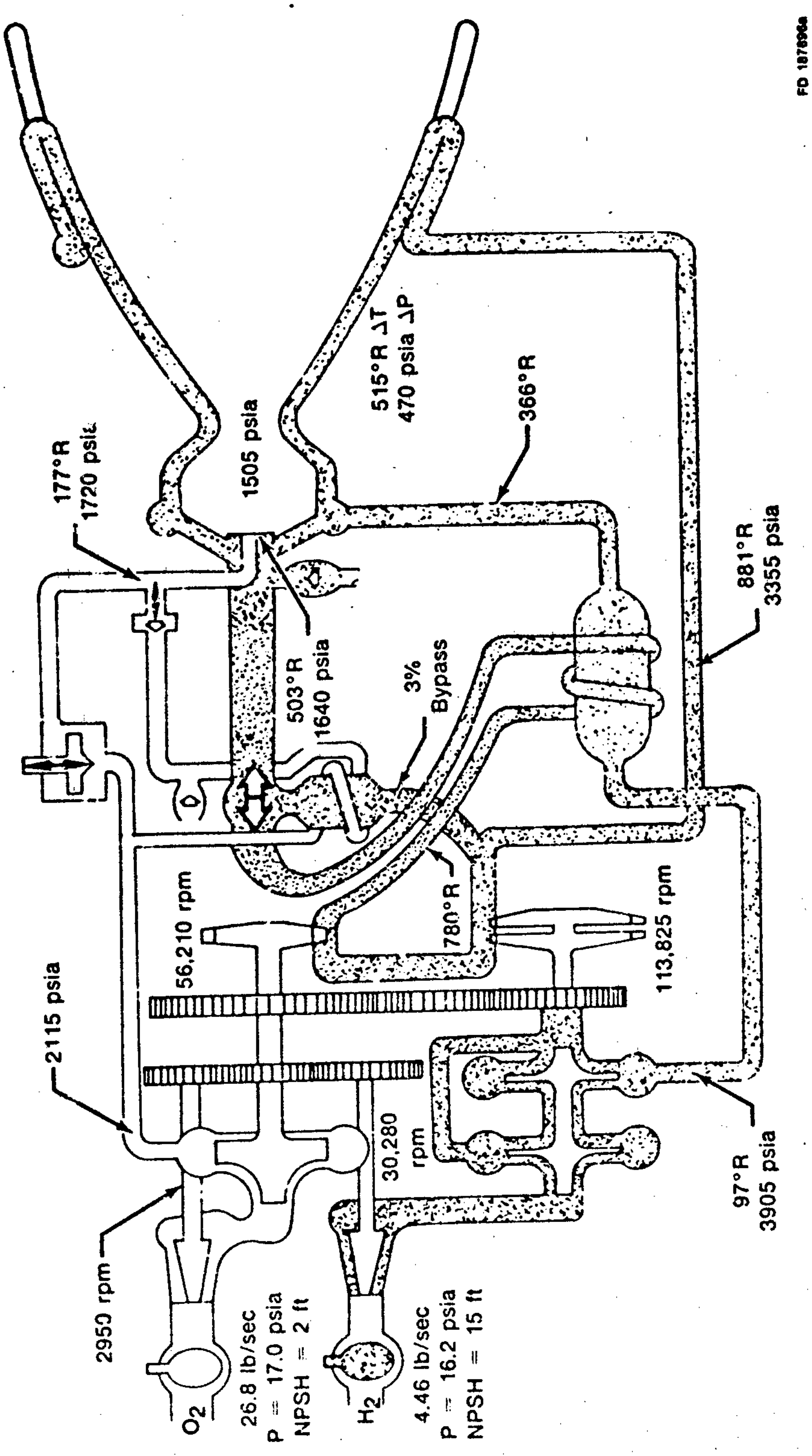


Figure 2-7. Advanced Expander Propellant Flow Schematic — Full Thrust (MR = 6.0)

2.2.2 Parametric Data

The parametric performance levels of the RL10 Derivative engines defined in 1973 were updated to reflect improvements in JANNAF prediction techniques and then adjusted to correlate with high-area-ratio nozzle performance test data generated with the RL10 and ASE engines. Also generated were parametric engine data (performance, weight, envelope, and cost) based on study ground rules (e.g., 1980 state-of-the-art, performance-optimized, man-rated reliability) for advanced expander and staged combustion cycle engines. Preliminary cycle studies were conducted which defined the ground rules. A viable engine configuration was selected for each basic cycle, and the parametric data was generated using these basic configurations as starting points.

Figure 2-8 shows specific impulse, weight, and overall diameter for the RL10 Derivative and Advanced Expander engines as a function of retracted engine length. This figure indicates the growth potential of the expander cycle by showing how specific impulse has increased from 459.8 sec for a 1960's technology engine (Derivative II) to 471.7 sec for a 1970's technology engine (Category IV) to 482.0 sec for the current technology engine.

Staged combustion cycle and advanced expander cycle performance characteristics as a function of thrust level are shown in Figure 2-9. As shown, there is no significant difference in performance for the two cycles.

2.2.3 Advanced Expander Optimization

A prepoint design study was performed to optimize thrust chamber geometry and cooling, engine cycle variations, and controls for an advanced expander engine. Performance was optimized for thrust levels of 10, 15, and 20K lb at a mixture ratio of 6:1 and an engine retracted length of 60 in. Variations in component design and the combustion chamber/primary nozzle configuration were studied to evaluate possible performance improvement. A summary of the results of the cycle optimization is presented in Table 2-2. An open loop, passive control system was selected for the engine to provide high reliability. Optimum chamber length was determined to be 15 in., and the optimum contraction ratio was found to be approximately 4:1, as shown in Figures 2-10 and 2-11. A preliminary point design engine cycle was determined for each of the three thrust levels, and power balance points were generated. Figure 2-12 shows chamber pressure and specific impulse characteristics for these preliminary design points.

2.2.4 Expander Cycle Low Thrust

RL10 derivative and advanced expander cycle engine characteristics at low thrust were examined to determine the effect of extended low-thrust operation. The impacts on critical components and engine life were defined, and performance characteristics were generated. No modifications to the engines were required to enable extended operation at low thrust. Kitting of critical engine components for the advanced expander cycle engine was also investigated. And, while it appears that performance, weight, and/or reliability gains are achievable, it must be determined if kitting specifically for low-thrust missions is economically justified. The available gain and cost of kitting are provided in Table 2-3. Expander cycle performance characteristics at low thrust are shown in Figure 2-13.

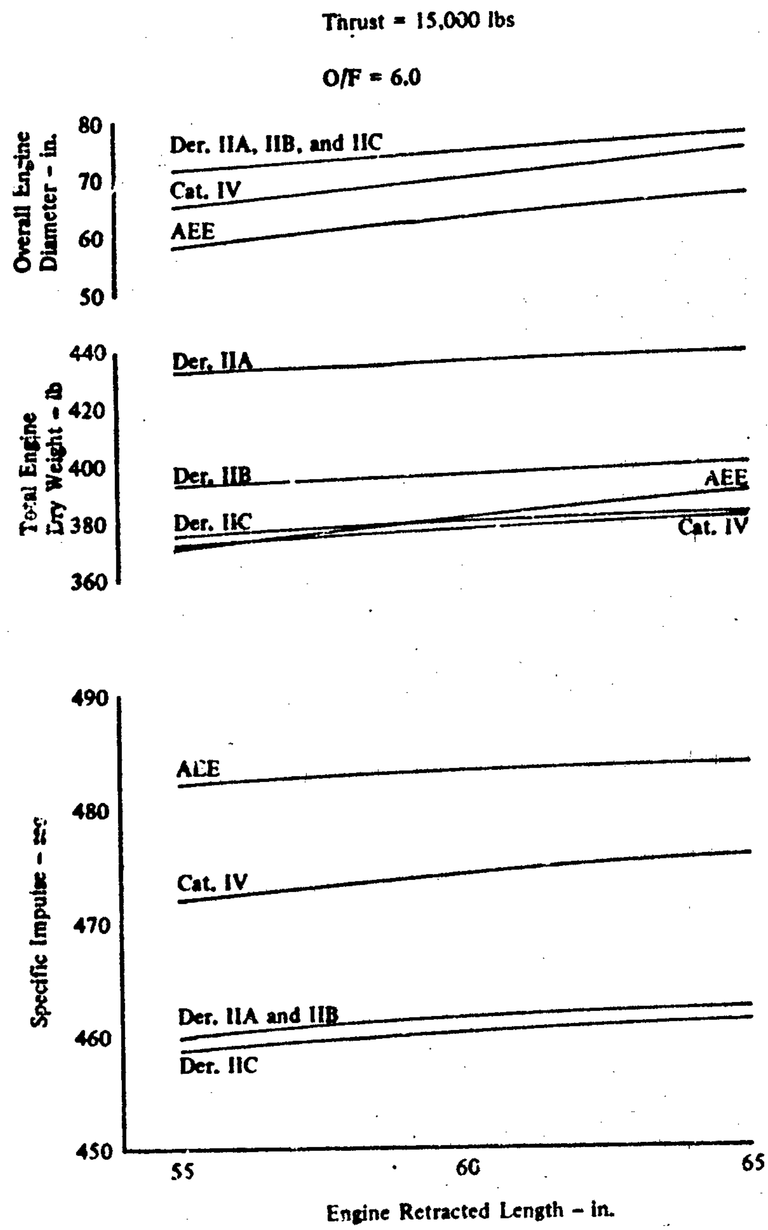


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Figure 2-8. Performance Charcteristics for Expander Cycle Engines

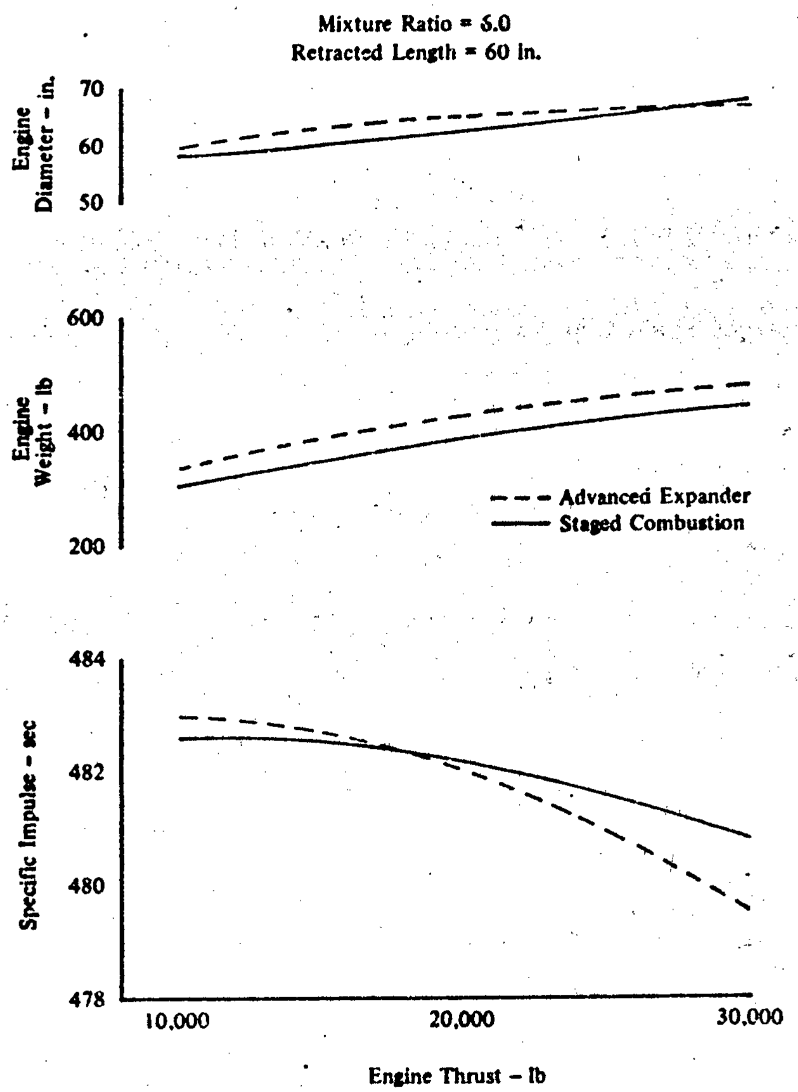

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Figure 2-9. Advanced Engine Performance Comparison

TABLE 2-2. ADVANCED EXPANDER ENGINE COMPONENT OPTIMIZATION

Configuration Change from Baseline Engine	*ΔPerformance Effect*	*Comments*
2- to 3-Stage Fuel Pump (10K thrust)	Pc = +140 psi Isp = +0.9 sec Wt = +7 lb Payload = +82 lb	Not incorporated because performance increase does not justify added cost and complexity.
115,000 to 150,000 Fuel Pump Speed (10K thrust)	Pc = +100 psi Isp = +0.7 sec Wt = −12 lb Payload = +110 lb	Not incorporated because performance increase does not justify added cost and complexity.
40% to 50% Regenerator Effectiveness (15K thrust)	Pc = +130 psi Isp = +0.6 sec Wt = +14 lb Payload = +36 lb	Effectiveness must be limited to keep chamber coolant temperature low enough to meet engine life requirements.
Series Turbines to Parallel Turbines (15K thrust)	Pc = −25 psi Isp = −0.2 sec Wt = −3 lb Payload = −15 lb	Not incorporated because of slightly lower performance and increased flow control complexity.
Parallel to Counter Chamber Coolant Flow Routing (15K thrust)	Pc = −310 psi Isp = −3.3 sec Wt = +5 lb Payload = −416 lb	Not incorporated because of lower performance.

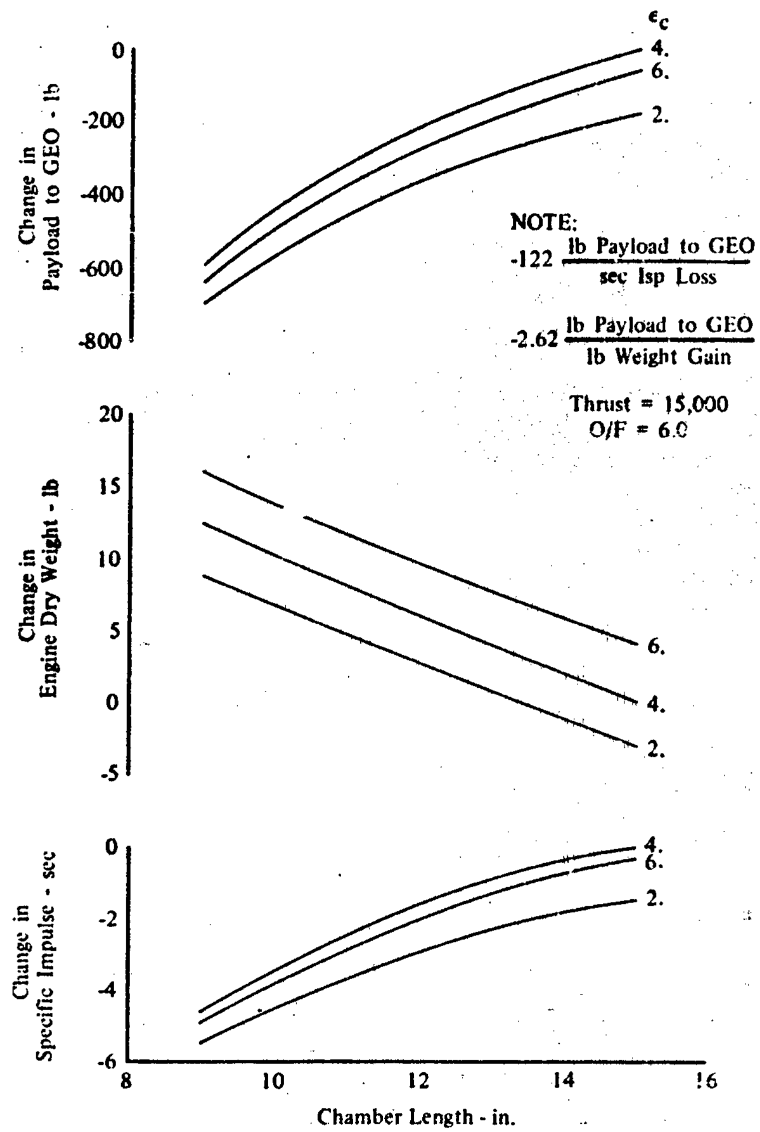

Figure 2-10. Chamber Configuration Effects on Advanced Expander Engine Performance

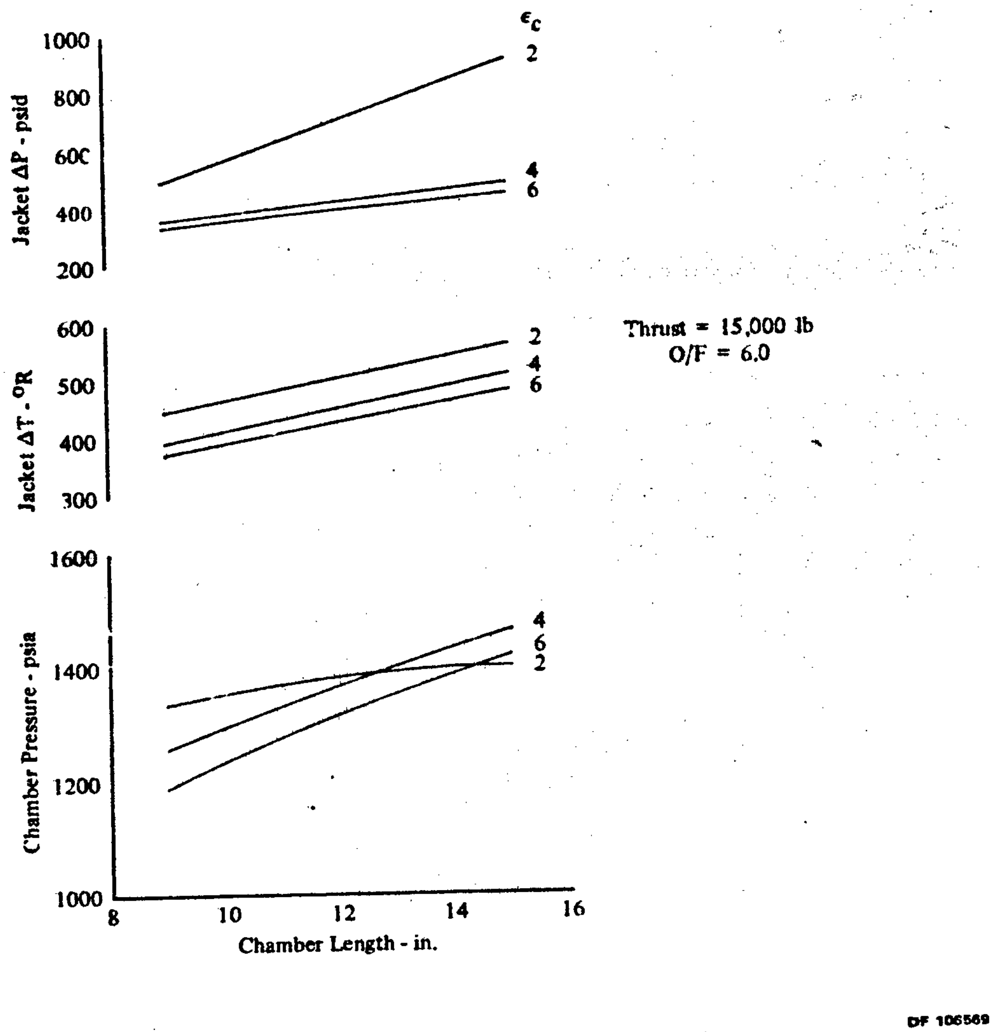

Figure 2-11. Chamber Configuration Effects on Advanced Expander Engine Cycle

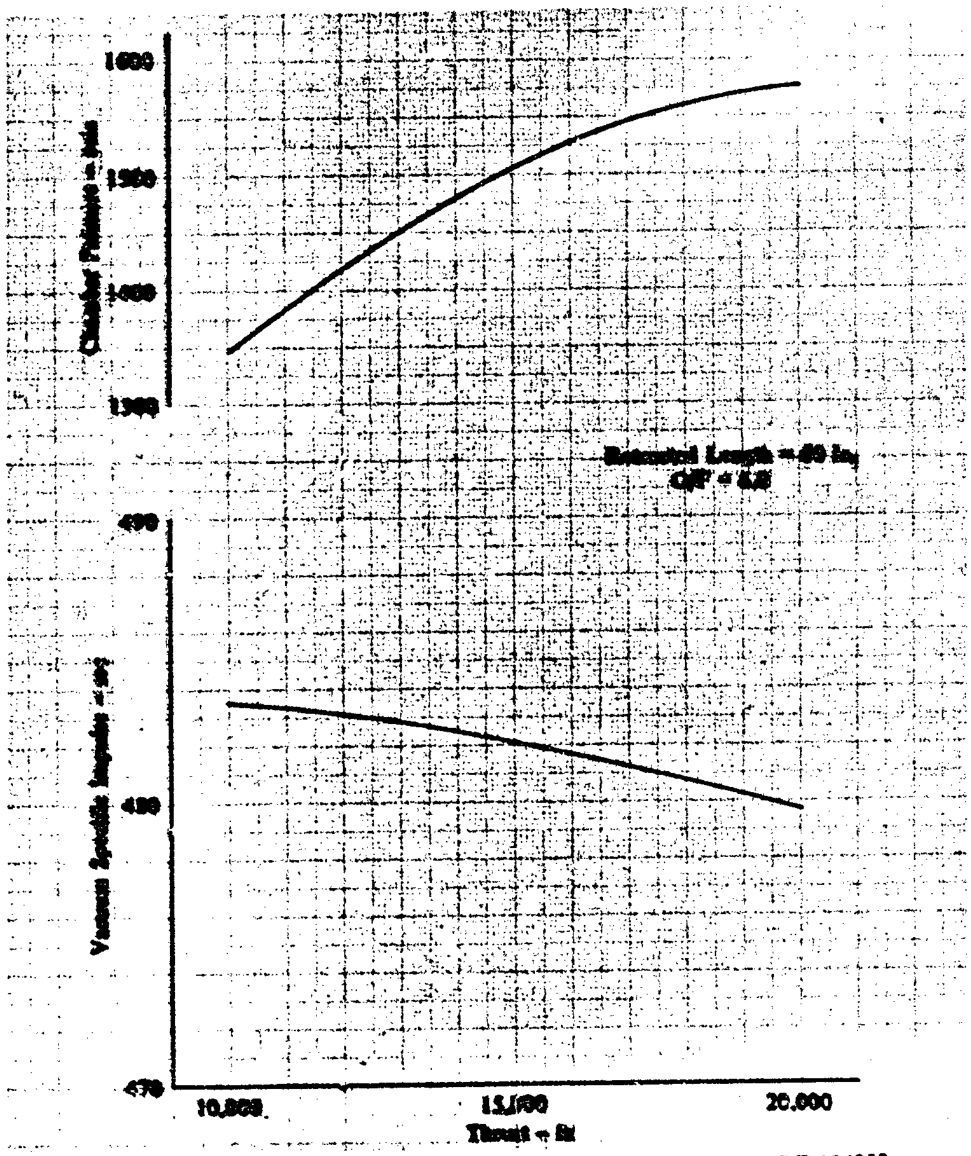

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Figure 2-12. Advanced Expander Cycle Optimization Results

TABLE 2-3. KITTED BASELINE ENGINE SUMMARY

	Component Kitted	*Effect*	*Weight Change (lb)*	*Cost Impact DDT&E ($M)*	*Cost Impact Production ($M)*
1.	Controls	Increased Reliability	−16	+1.0	+0.1
2.	Chamber/Nozzle	Optimized Design; +14.5 sec Isp	−35	+52	+0.6
3.	Regenerator Redesign	Optimized Design	−18	+1.5	+0.1

Note: 1. Costs are rough-order-of-magnitude in FY '79 millions and are increases above baseline engine DDT&E levels not considering required consumables or facility modifications.

2. Production costs are per engine cost based on a buy of 50 kitted engines.

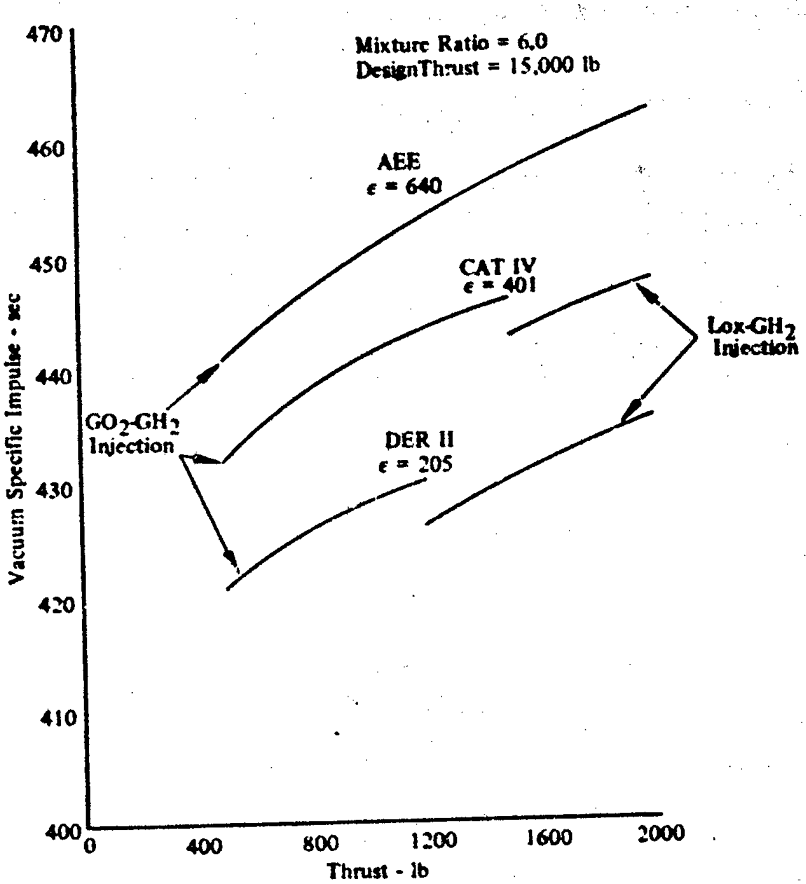

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Figure 2-13. Expander Cycle Low Thrust Performance

2.2.5 Program Plans

Development plans established for modified 15,000-lb thrust RL10A-3-3 engines (Derivatives IIA and IIB) and optimized expander cycle RL10 engine (Category IV) in the 1973 Contract NAS8-28989 "Design Study of RL10 Derivatives" were used as the basis for the plans presented here. Plans were adjusted to reflect the procurement lead times currently being experienced and any new information available. A program plan for the new 15,000-lb thrust Advanced Expander Cycle engine was generated during this study.

The engine development program approach, used in the program planning for the Contract NAS8-28989 study, was based on design verification specifications (DVS) which specify the design requirements and method of verifying these requirements for the baseline RL10 Derivative engines (Derivatives IIA and IIB). DVS's were not generated for the Category IV engine, but an estimate of the verification program for this engine was made. The Advanced Expander Cycle engine program was estimated in a similiar manner. The DVS's establish a minimum development program because the assumption is made that the development program is "success oriented," and only one design, build, test cycle through engine Final Flight Certification is required. Knowing that previous RL10 and other rocket engine (e.g., F-1 and J-2) development programs have not been accomplished in a single cycle, a redesign and reverification effort has been considered in the total engine development program plans. The total development program effort planned for each engine design was based on data and experience from previous RL10 engine programs. The redesign and reverification effort was determined by estimating the DVS requirements and deducting these from the total engine development program requirements.

Preliminary program plans were developed for each baseline engine design configuration for the total development through Final Flight Certification (FFC). Program planning was based on DVS's formulated for those RL10 engine components not already qualified, i.e., components that are not of the same configuration as those used in the operational RL10A-3-3 engine that is currently used in the Centaur launch vehicle. As stated above, a redesign and reverification effort was included to achieve a realistic total engine development program. The major milestones and key decision points, as well as other significant activities of these programs, were derived, and the durations established for the specified tasks. The number of hardware components and engines required in equivalent engine sets, and the number of engine tests were specified for both the DVS program requirements and the total development program requirements.

Test facilities required for engine development and Ground Support Equipment development were identified. Other end items, including packaging, preservation, handling and mock-up activities were also specified.

Budgetary and planning cost estimates for each baseline engine Category (Derivative IIA, IIB, IIC, Category IV and Advanced Expander) are presented in Volume III of this Report. These cost estimates were determined for the development engine programs, the production programs, including the first production unit, and the Operational and Flight Support programs.

The development plans for the RL10 Derivative IIB and the Advanced Expander cycle engine are given in the following sections.

2.2.5.1 RL10 Derivative IIB Engine

The development program for the baseline Derivative IIB engine will require about 59 mo of design, fabrication, and test effort. This effort will encompass three design, build, test cycles to FFC (Initial, PFC and FFC configurations). Figure 2-14 depicts the development schedule, presenting the major program milestones and key decision points as well as the total engine development program. The design and fabrication schedules for this program are shown in Figure 2-15, and the program test plan is shown in Figure 2-16.

Preliminary DVS documents were generated during the previous study for the new and modified RL10A-3-3 components, which require design verification for the baseline Derivative IIB engine.

The DVS's establish the program requirements in terms of numbers of hardware and tests for testing levels estimated for verification of the components and engine design at PFC and FFC. The requirements specified in these documents are based on verifying a single design with no redesign iterations. From the preliminary component and engine DVS design and verification requirements, about 9 equivalent engine sets of hardware, 53 engine builds (including rebuilds), and 500 engine tests were determined to be necessary to accomplish the baseline Derivative IIB verification program objectives through Final Flight Certification. The estimate for redesign and reverification is about 40% of the total development effort. It was estimated that about 48 mo would be necessary to accomplish the baseline Derivative IIB engine development DVS program component and engine design, fabrication, assembly and test verification requirements.

It was estimated that about 750 engine tests over a period of 32 mo, combined with a 27-mo design support, fabrication, and initial component test period, would be necessary to accomplish the total baseline Derivative IIB engine total development program objectives. Duration of the overall development effort is estimated at 59 mo. These total program requirements are based on previous RL10 engine modification history and similar concept history, and current material lead time. Development of the RL10A-3-3 engine model required about 1,000 engine tests during the 24-mo test period, and a 33-mo overall development program duration.

Five active engines were selected for the Derivative IIB engine development program based on the above considerations and particular characteristics of the expander turbine power cycle. A total of about 80 engine builds and rebuilds will be used for the Derivative IIB engine total development program as compared with 175 for the equivalent RL10A-3-3 development program. About 23 equivalent engine sets of hardware are planned to support the total assembly and test programs.

Fabrication and testing of the Derivative IIB engine will be accomplished in the existing RL10A-3-3 facilities. To accomplish the engine test program, two vertical test stands, E-6 and E-7, will be used. Test stand E-6 is now used for acceptance testing of the operational RL10A-3-3 engines being delivered to the NASA-LeRC for Centaur and will be used in this program for testing Derivative IIB engine with a primary nozzle, i.e., without a nozzle extension. Test stand E-7, now inactive, will be reactivated for the tank head idle thrust, pumped idle thrust, and full thrust level engine testing of engines with a truncated nozzle extension. The major stand special test equipment, that is planned for installation in E-7 test stand, is required to provide an accurate simulation of predicted propellant conditions under the zero gravity conditions encountered in space.

The high-area-ratio nozzle engine testing can be accomplished in a high-altitude facility such as the Arnold Engineering and Development Center (AEDC) test stand J-3. It is necessary to make modifications to these stands to make them operational for this testing. For this development program the AEDC J-3 test stand was considered the baseline.

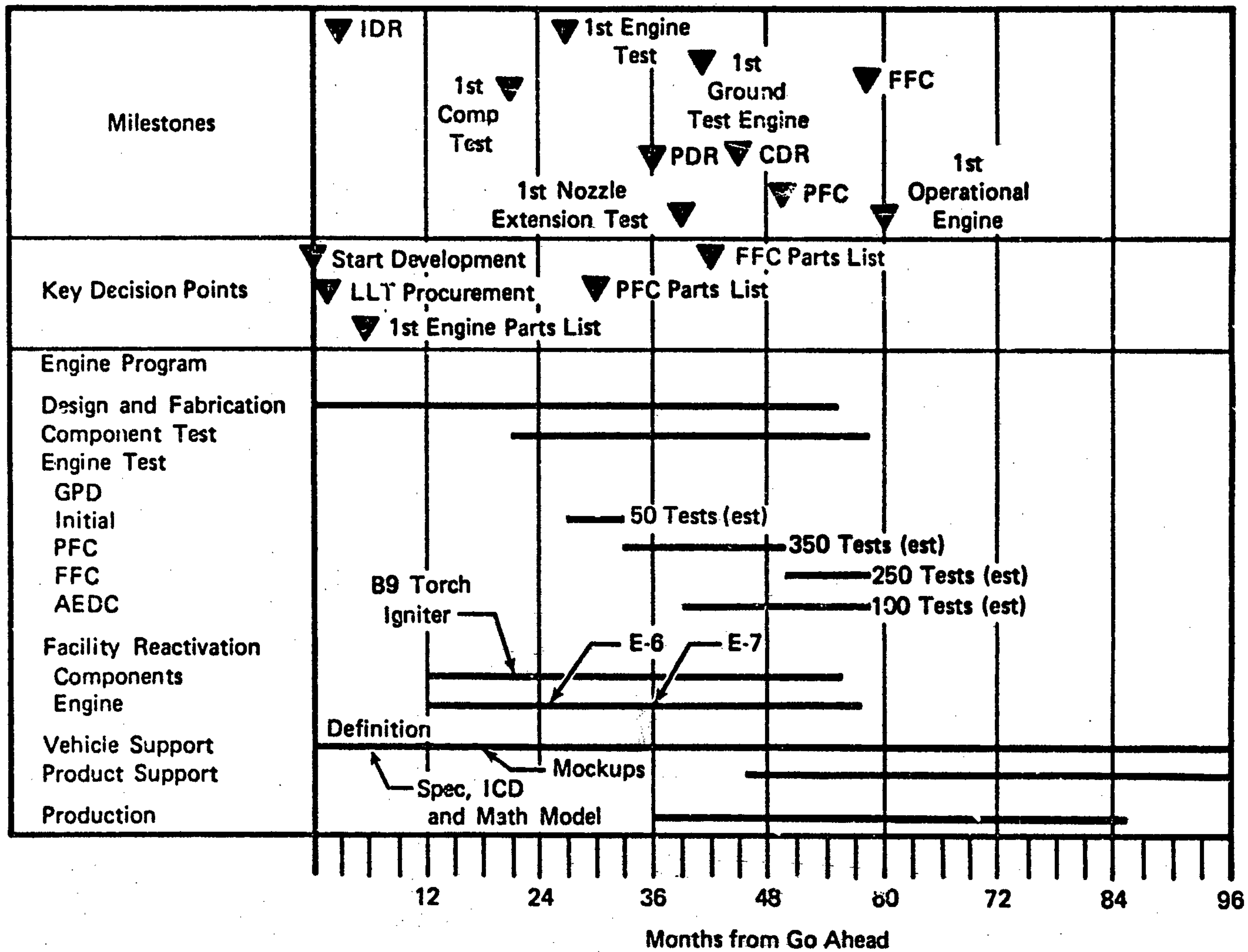

Figure 2-14. Baseline Derivative IIB Engine Total Development Program

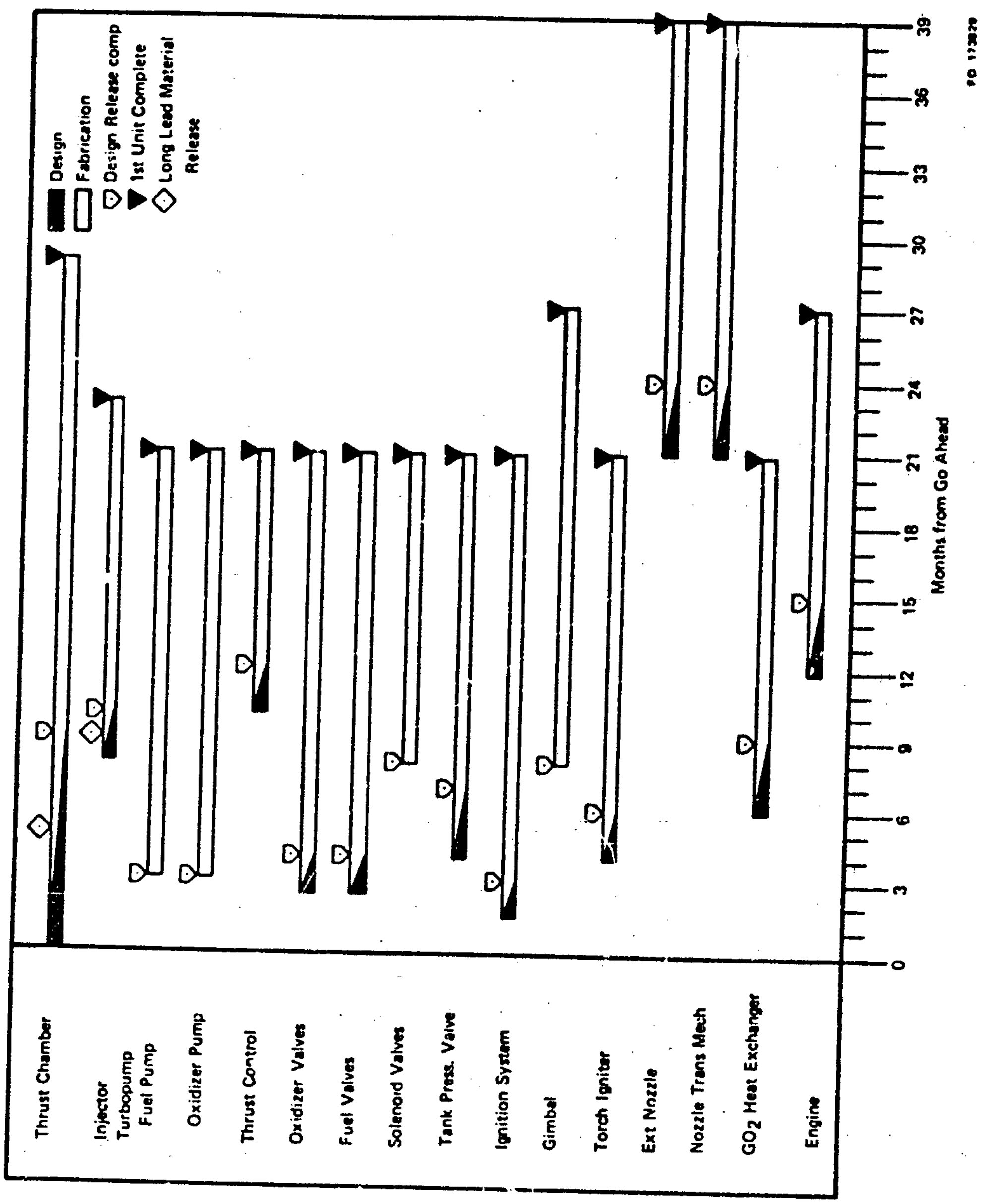

Figure 2-15. Derivative IIB Fabrication Schedule, First Development Unit

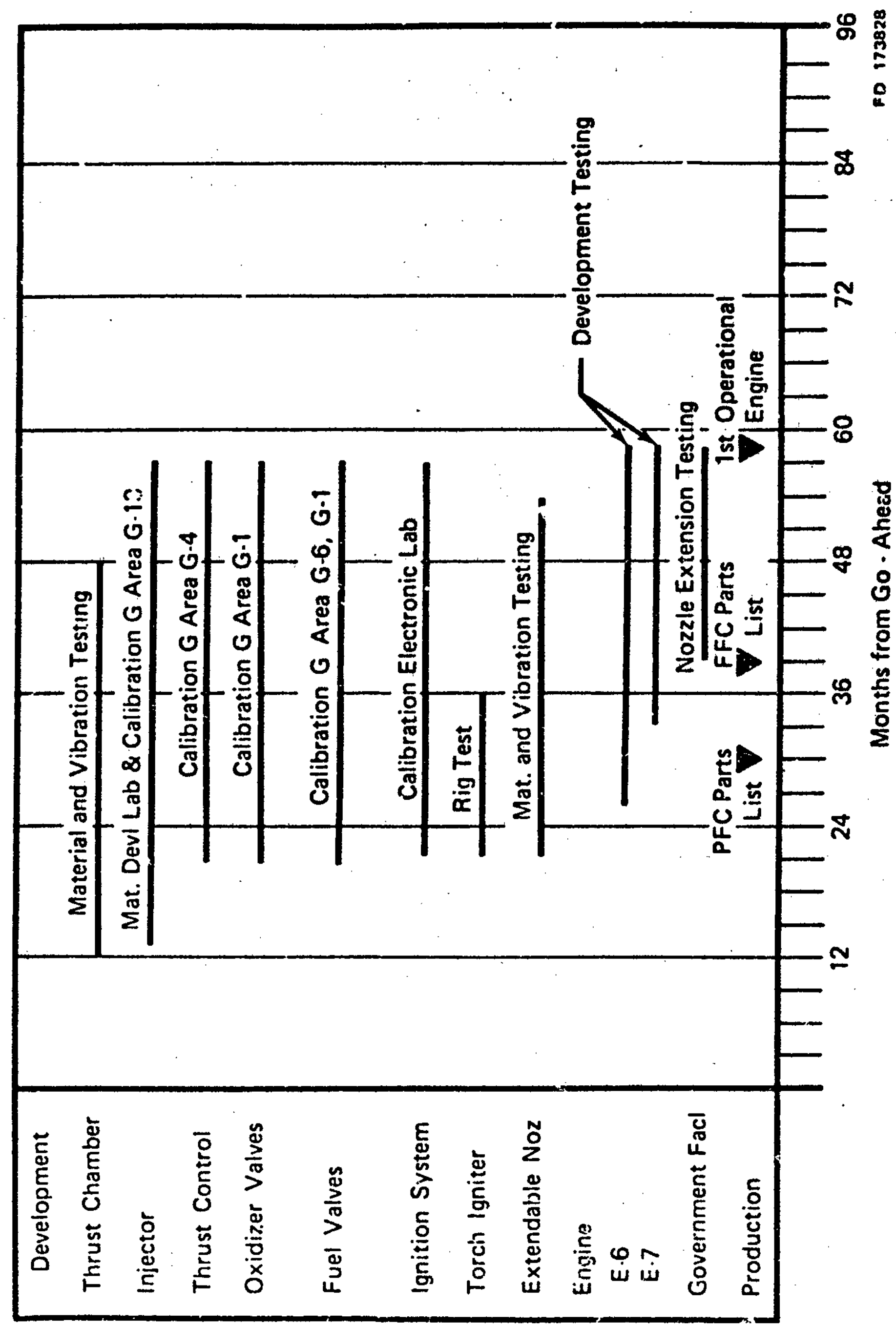

Figure 2-16. Derivative IIB — Development Program Total Test Plan

2.2.5.2 Advanced Expander Cycle Engine

The development program for the baseline Advanced engine design consists of 89 mo of design, fabrication and test effort. This effort encompasses three design build-test cycles to FFC; i.e., initial, Preliminary Flight Configuration (PFC), and Final Flight Configuration (FFC). The development schedule showing the major program milestones, key decision points, and the total engine development program is shown in Figure 2-17. The baseline Advanced Expander Cycle engine design and fabrication schedules are shown in Figure 2-18.

Major component testing will be initiated with high-pressure fuel turbopump and oxidizer turbopump and bearing testing followed by low-pressure fuel and oxidizer pump, valve and control system testing. Engine testing will begin 36 mo after start of development.

Although DVS's were not formulated as a part of the Advanced Expander Cycle engine development program plan, an estimate of the DVS program requirements was made. This was made from DVS requirements comparison of the Advanced Expander Cycle engine configuration with the engineering judgment to upgrade the Derivative II engine DVS requirements to a level comparable to Advanced Expander Cycle engine DVS requirements. The resulting DVS program requirements necessary for the Advanced Expander Cycle engine are 15 equivalent sets of engine hardware, 108 engine builds (including rebuilds), and 750 engine system tests. Eight active engines (for a total of 180 engines, including rebuilds), were selected for the total development program. About 40 equivalent engine sets of hardware are needed to support the total assembly and test program.

It was estimated that about 72 mo would be necessary to accomplish the baseline Advanced Expander engine DVS program component and engine design, fabrication, assembly, and test verification requirements.

Historical RL10 design, fabrication, and test experience formed the basis for estimating the duration of the overall baseline Advanced Expander Cycle development and the number of engine tests required. It was estimated that about 1250 engine tests over a period of 53 mo, combined with a 36-mo design, fabrication, and initial component test period, will be necessary to accomplish the baseline Advanced Expander Cycle engine development program objectives. Duration of the overall development effort is estimated at 89 mo. RL10 engine development to the first RL10 Preliminary Qualification required about 1,200 engine tests and a 64-mo development program.

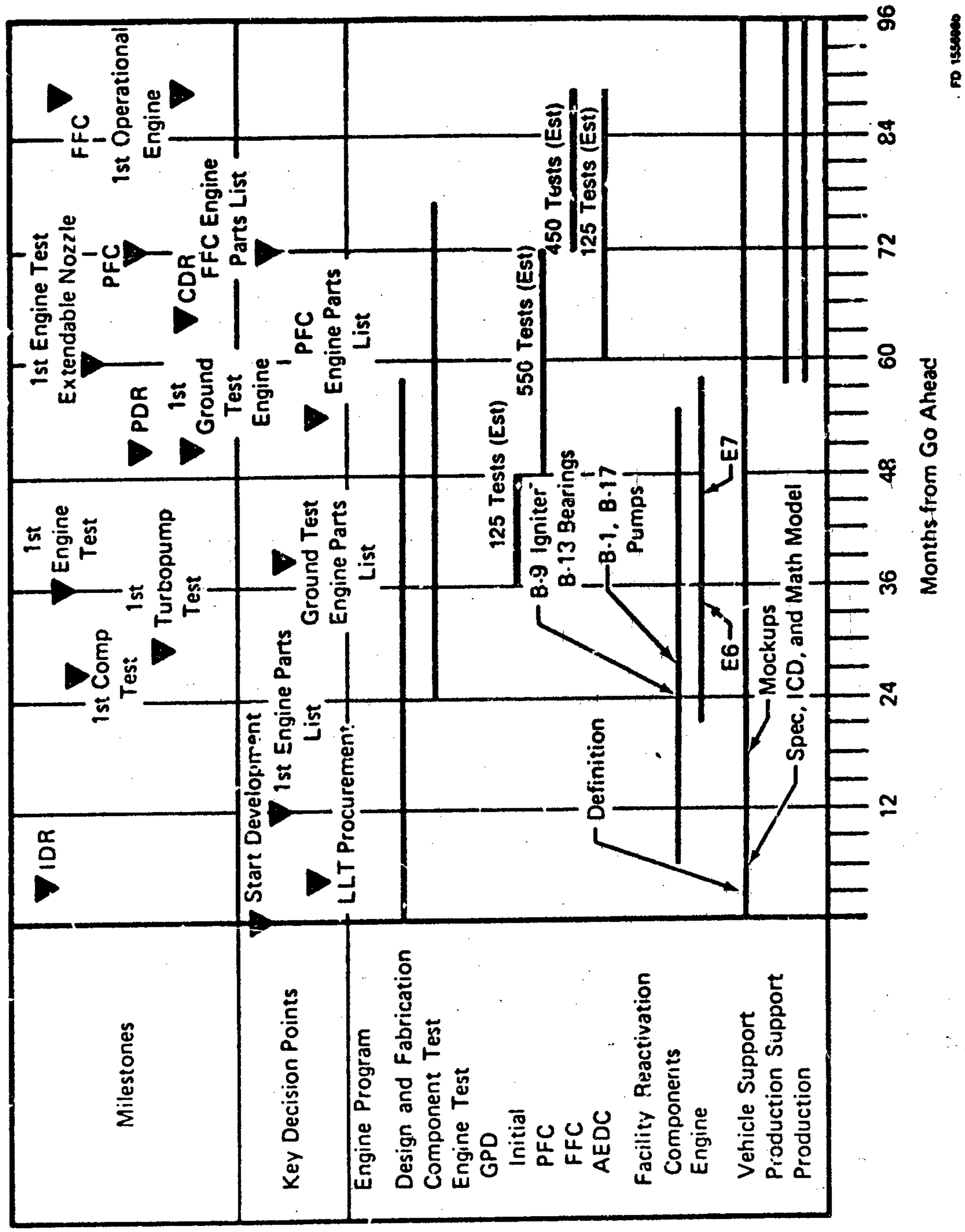

Figure 2-17. Advanced Expander Cycle Engine Development Schedule and Major Program Milestones

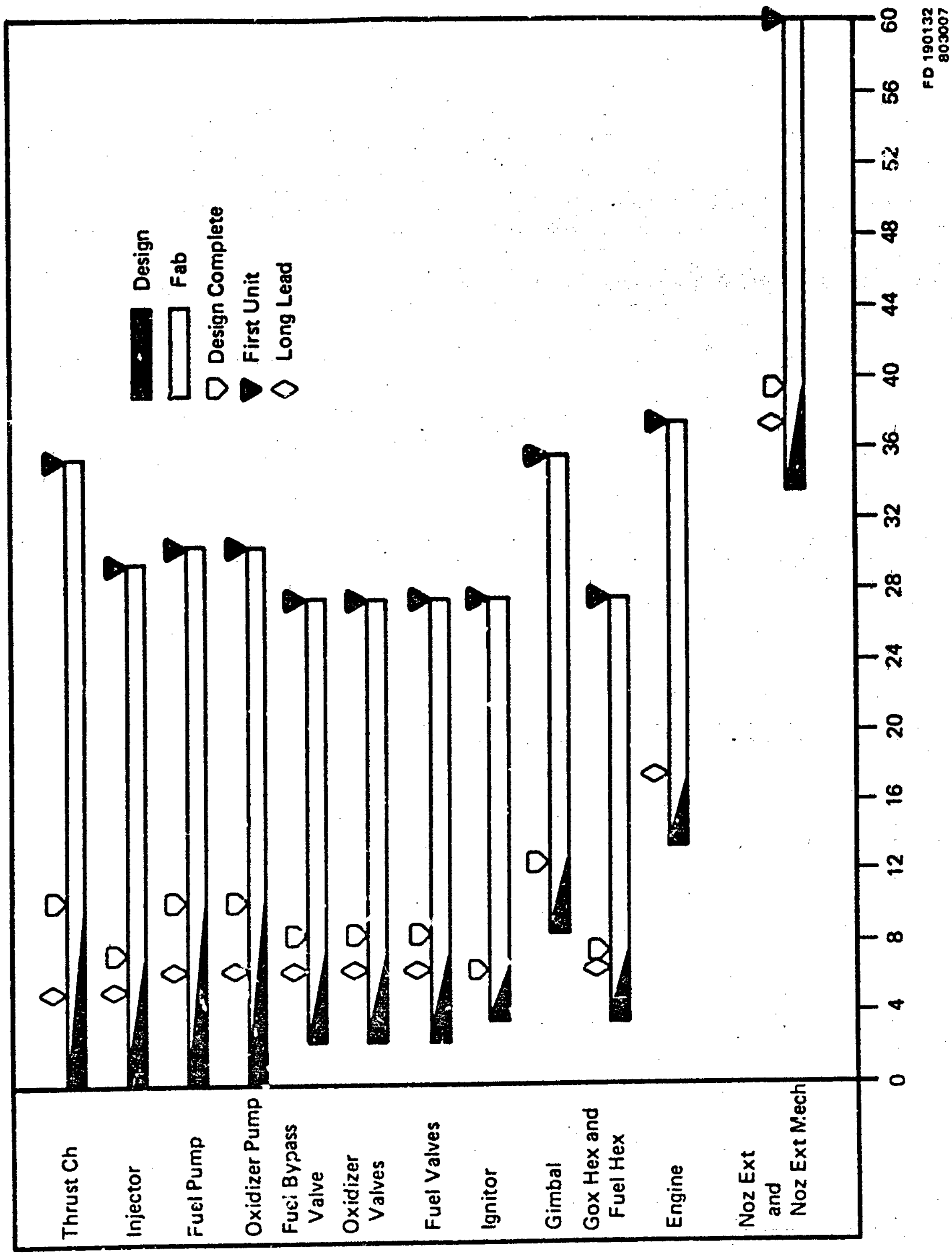

Figure 2-18. Advanced Expander Cycle Engine Fabrication Schedule

2.2.6 Safety and Reliability Comparisons

Crew safety and mission reliability are important considerations in the selection of an engine configuration for the OTV. As part of this study, parametric curves of mission and crew safety reliability as a function of engine reliability were generated for 1-, 2-, and 3-engine vehicles with and without engine-out capability. The results are shown in Figure 2-19, and the assumptions used in this analysis were:

- 10% of all main engine failures will destroy adjacent engine(s) but not damage the remainder of the vehicle including the auxiliary propulsion system (APS).
- 5% of all main engine failures will disable the vehicle
- The APS has same reliability as main engine(s)
- No rescue facilities are available
- 6 burns are required to complete mission
- 3 burns are required to save crew
- No vehicle damage results from APS failure.

Of the eight configurations presented in Figure 2-19, a two-engine system with an engine-out safety capability and a single-engine system with an APS safety backup provide the highest combined crew safety and mission reliability levels. This figure also illustrates that engine reliability near the present RL10 demonstrated reliability and 0.9982 (90% lower bound confidence) is probably necessary to provide mission and safety reliability.

A failure mode comparison and engine reliability comparison was made for the optimum Advanced Expander Cycle Engine defined in this study and the Staged Combustion Cycle Engine defined in Contract NAS8-32996.

A failure mode and effects analysis was completed for the advanced expander cycle, and 66 failure modes were identified. This number of failure modes is essentially the same as for the RL10 engine. Four of these failure modes were identified as being likely to cause complete system loss or major system damage. Based on this number of hazardous failure modes it was estimated that 6% of the failures would result in damage to an adjacent engine, and 3% would damage the vehicle.

Design features and operating characteristics for the staged combustion engine were then compared to those of the advanced expander engine to identify relative failure modes. The staged combustion engine was found to have at least 109 failure modes with 33 of these likely to cause complete system loss or major system damage. Based on this information it was estimated that 30% of the failures would result in damage to an adjacent engine, and 15% would damage the vehicle. The number of failure modes estimated for the staged combustion engine is probably low since sufficient information was not available to make a detailed evaluation of its control system, and many more failure modes exist in that area. An engine's reliability is related to the number of potential failure modes and engine configuration (e.g., control system, cycle, etc.). Since the RL10 is similar to the advanced expander cycle engine in these areas, estimated engine reliability was determined based on RL10 experience. The staged combustion engine configuration (from Contract NAS3-32996) is similar to the SSME (e.g., control system, cycle, etc.) and is expected to have a similar number of failure modes.

Configuration	Mission Reqm't	Safety Reqm't	Mission Rel	Safety Rel
1 Main Engine	1 ME	1 ME	M1	S1
1 Main Engine, 1 APS	1 ME	1 ME or APS	M2	S2
2 Main Engines	2 ME	1 ME	M3	S3
2 Main Engines	1 ME	1 ME	M4	S4
2 Main Engines	2 ME	2 ME	M5	S5
2 Main Engines, 1 APS	2 ME	1 ME or APS	M6	S6
3 Main Engines	2 ME	1 ME	M7	S7
3 Main Engines	3 ME	2 ME	M8	S8

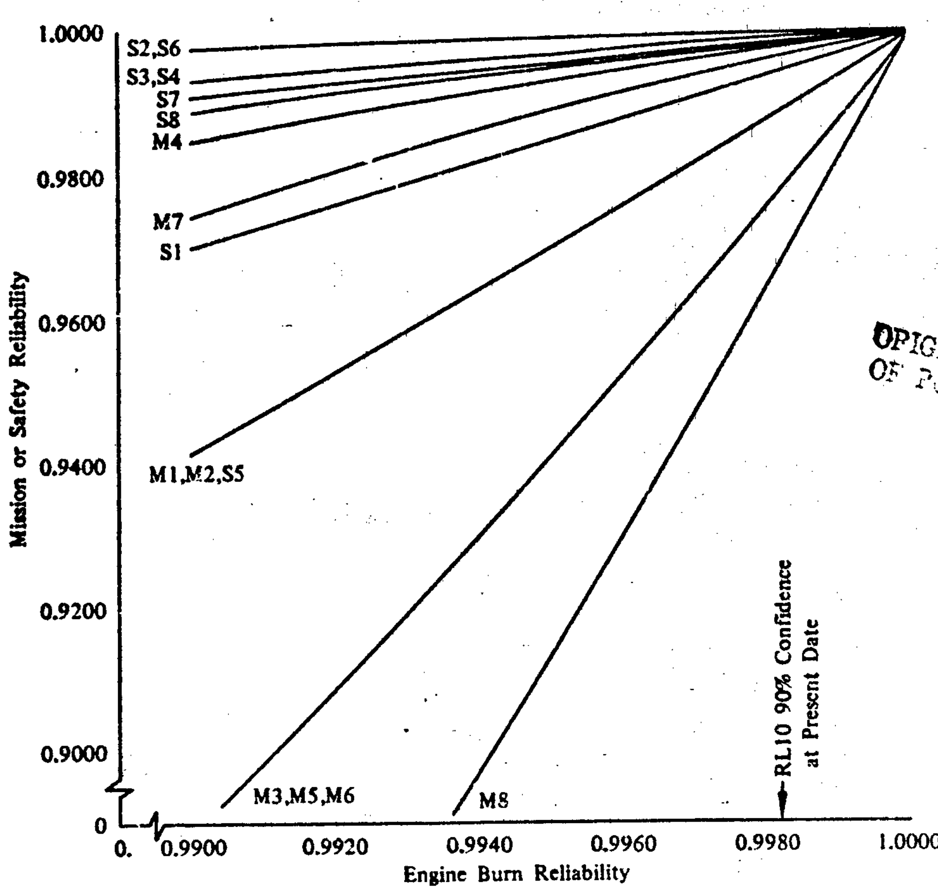

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Figure 2-19. Impact of Configuration on OTV System Reliability

Therefore, the estimated engine reliability for the staged combustion configuration was based on SSME experience. Estimated reliability at FFC for the advanced expander engine is 0.9967, and for the staged combustion engine 0.9898. Crew safety and mission reliability were estimated for both engine cycles, and the results are shown in Figure 2-20. They indicate that both crew safety and mission reliability will be significantly higher with the advanced expander engine. While the absolute levels may not be exact, the relative levels and trends should be indicative of the differences that exist between the two engine cycles.

Configuration	Mission	Safety	Mission Reliability	Safety Reliability
1 Main Engine, 1 APS	1 ME	1 ME or APS	M2	S2
2 Main Engines	2 ME	1 ME	M3	S3

Assumptions:

- 30% of main engine failures for staged combustion cycle destroy adjacent engine but not APS
- 6% of main engine failures for advanced expander cycle destroy adjacent engine but not APS
- 15% of main engine failures for staged combustion cycle disables spacecraft (APS)
- 3% of main engine failures for advanced expander cycle disables spacecraft (APS)
- APS is equally reliable as main engine
- No rescue facility
- 6 burns/mission - 3 burns/safety mission

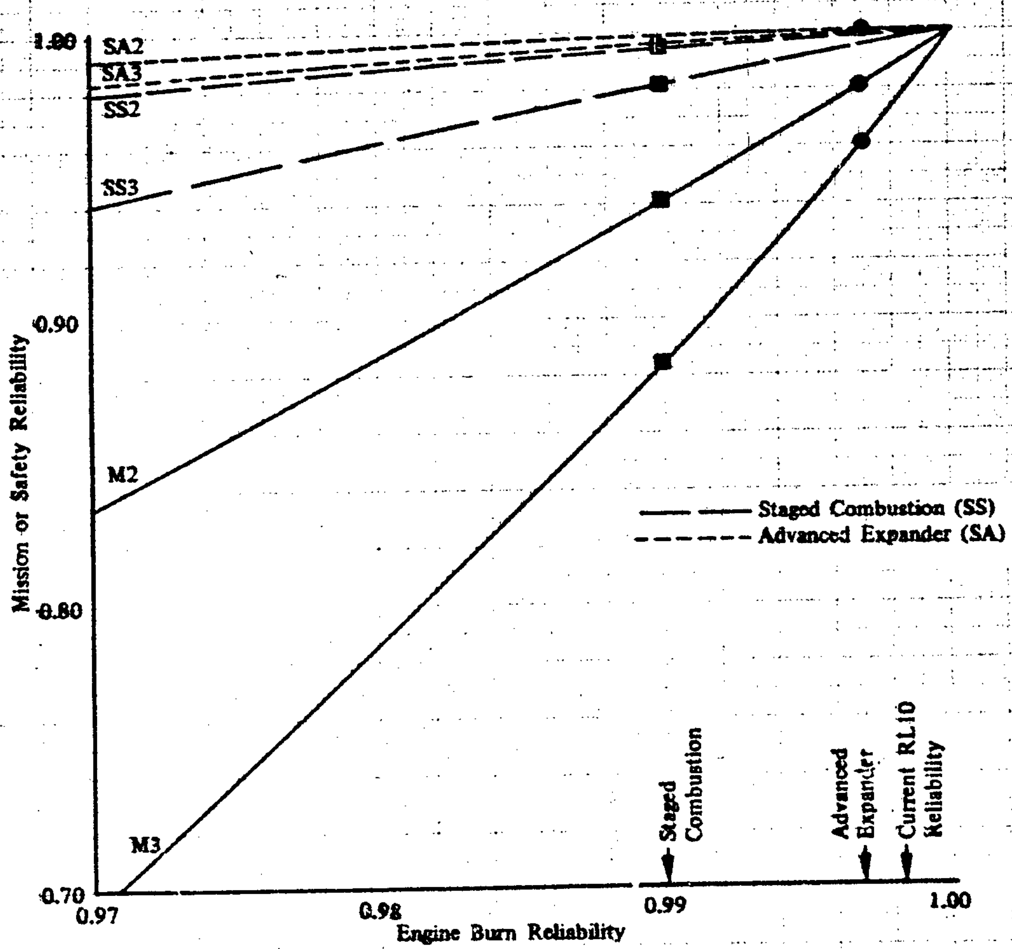

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Figure 2-20. OTV Reliability With Advanced Engines

SECTION 3

CONCLUSIONS

1. The RL10 and its derivatives are the only high-performance upper-stage engines that can be operational in the 1980's.

2. RL10 Derivative engines have a specific impulse that is within 4% of all OTV advanced engines.

3. RL10 Derivative engines can provide the highest demonstrated reliability for OTV applications.

4. An expander cycle engine is inherently more reliable than a staged combustion cycle engine. For example, the estimated single burn demonstrated reliability of the advanced expander cycle engine considered in this study is 0.9967 (at FFC) while the staged combustion cycle engine demonstrated reliability was estimated to be 0.9898.

5. There is no significant performance difference between advanced expander and staged combustion cycle engines.

6. The expander cycle engine provides as much potential for performance growth as a staged combustion cycle engine for OTV applications.

7. A high-thrust expander cycle engine provides good performance and long life at low-thrust operating conditions with no need for kitting.

8. There is a substantial difference in development cost between the advanced expander cycle and staged combustion cycle engines.

SECTION 4

RECOMMENDATIONS

1. Work should be initiated on RL10 Derivative engines to support a 1987 OTV operational capability.*

2. Further OTV system definition work should be accomplished to better define engine/vehicle interface requirements and sensitivities in areas such as low thrust operating requirements and full thrust NPSH levels.

3. Component technology programs should be initiated in composite materials, the thrust chamber/nozzle and fuel turbopump areas leading to a data base on these critical items on which an advanced expander cycle engine design can be based.

4. The staged-combustion cycle should be dropped from further consideration for advanced OTV applications due to its complexity, higher cost, lower reliability, and no significant performance difference when compared to an advanced expander cycle engine.

*See P&WA FP 80-807, RL10/RL10 Derivative Engine Program for the 1980's, 3 March 1980.